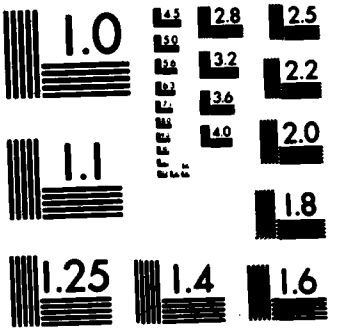
AD-A146 135 SPREAD-SPECTRUM COMMUNICATIONS(U) ILLINOISUUNIV AT URBANA COORDINATED SCIENCE LAB M B PURSLEY ET AL. 07 AUG 84 ARO-15492.15-EL DAAG29-78-G-0114 1/1

UNCLASSIFIED F/G 9/4 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ARO 15492.15-EL

ARO 18103.18-EL

(2)

UNCLASSIFIED
SECURITY CLASSIFICATION

AD-A146 135

DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: NONE
2a. SECURITY CLASSIFICATION AUTHORITY: N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release, distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): N/A
6a. NAME OF PERFORMING ORGANIZATION: Coordinated Science Laboratory, University of Illinois; 6b. OFFICE SYMBOL (If applicable): N/A	7a. NAME OF MONITORING ORGANIZATION: U. S. Army Research Office
6c. ADDRESS (City, State and ZIP Code): 1101 W. Springfield Avenue, Urbana, IL 61801	7b. ADDRESS (City, State and ZIP Code): Post Office Box 12211, Research Triangle Park, NC 27709
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: U.S. Army Research Office; 8b. OFFICE SYMBOL (If applicable): N/A	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Grant DAAG29-78-G-0114, Contract DAAG29-81-K-0064
8c. ADDRESS (City, State and ZIP Code): Post Office Box 12211, Research Triangle Park, NC 27709	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
N/A	N/A	N/A	N/A

11. TITLE (Include Security Classification): Grant DAAG29-78-G-0114 Final Report: Contract DAAG29-81-K-0064 SPREAD-SPECTRUM COMMUNICATIONS

12. PERSONAL AUTHOR(S): Michael B. Pursley and Dilip V. Sarwate

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final Report	FROM 5/21/78 TO 6/20/84	7 August 1984	8

16. SUPPLEMENTARY NOTATION: The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official department of the Army position policy, or decision, unless so designated by other documentation.

17. COSATI CODES		
FIELD	GROUP	SUB. GR.
	N/A	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This is the Final Report for Contract DAAG29-81-K-0064 (May 21, [illegible]-June 20, 1984) ARO Proposal 18103-EL), and the deferred Final Report for Grant DAAG29-78-G-0114 (May 21, 1978-May 20,1981) (ARO Proposal 15492-EL). Our progress during a 6 year investigation of spread-spectrum systems is outlined. A list of publications is included.

DTIC ELECTE S OCT 1 1984 D B

DTIC FILE COPY

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Professor Michael B. Pursley	217-333-2966	NONE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. UNCLASSIFIED

84 09 25 089

SECURITY CLASSIFICATION OF THIS PAGE

SPREAD-SPECTRUM COMMUNICATIONS

FINAL REPORT

Michael B. Pursley and Dilip V. Sarwate

7 August 1984

U. S. ARMY RESEARCH OFFICE

GRANT DAAG29-78-G-0114
CONTRACT DAAG29-81-K-0064

Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

Approved for public release; distribution unlimited

THE VIEWS, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHORS AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

DTIC COPY INSPECTED 2

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

FOREWORD

This is the Final Report for Contract DAAG29-81-K-0064 (May 21, 1981 - June 20, 1984), (ARO Proposal 18103-EL), and the deferred Final Report for Grant DAAG29-78-G-0114 (May 21, 1978 - May 20, 1981), (ARO Proposal 15492-EL). Our progress during a six-year investigation of spread-spectrum communication systems is outlined below. We are grateful to the U. S. Army Research Office for its generous support of this research program.

STATEMENT OF PROBLEM

We have studied the problems of system analysis and signal design for spread-spectrum communication systems. Emphasis has been on direct-sequence modulation schemes, frequency-hop schemes, and hybrid direct-sequence/frequency-hop schemes. We have studied waveform and signal designs, signal processing techniques, performance analysis techniques, bounds and approximations for error probabilities, bounds for signal and sequence parameters, and error-control techniques for spread-spectrum communication systems.

SUMMARY OF RESULTS

The results of our research can be categorized into results on the problem of computing error probabilities for spread-spectrum multiple-access systems, design and analysis of code sequences and waveforms for direct-sequence and frequency-hop spread-spectrum communication systems, frequency-hop spread-spectrum systems, and time-hopped communication systems.

Average Error Probability for Spread-Spectrum Multiple-Access Systems

We have developed bounds and approximations for the average probability of error for asynchronous direct-sequence spread-spectrum multiple-access (DS/SSMA) communication systems. Both upper and lower bounds have been obtained for the average error probability. These bounds are primarily useful for systems which have only a few simultaneously active transmitters, because the computational effort required to evaluate these bounds increases exponentially with the number of simultaneously active transmitters. On the other hand, the approximation to the average error probability is useful for systems with many simultaneously active users because the amount of computation required to evaluate the approximation grows only linearly with the product of the number of transmitters and the number of chips per data bit. The accuracy of the approximation is extremely good in most cases, and is certainly accurate enough for practical applications. The method has been employed to evaluate not only DS/SSMA systems with binary PSK modulation but also systems using quadriphase-shift-keying (QPSK), offset-QPSK, and minimum-shift-keying (MSK) modulation. Because of the similarities between multiple-access interference and specular multipath interference, many of these techniques can and have been employed to evaluate average error probabilities for direct-sequence spread-spectrum systems operating over specular multipath channels.

More recently, we have developed new methods for the evaluation of error probabilities in DS/SSMA systems in a computationally efficient manner. The results include new upper and lower bounds on the average probability of bit error for a correlation receiver. Nice features of these bounds are that they require only moderate computation, and the upper and lower bounds converge together as the amount of computation increases. Furthermore, the types of computations which are required to evaluate the bounds are particularly suited to an array processor. Applications to packet radio networks have been investigated.

Design and Analysis of Sequences for Spread-Spectrum Systems

We have investigated the effects of partial correlation on the performance of DS/SSMA systems. Investigation has primarily focused on systems in which the number of chips N per bit is either relatively prime to the period p of the signature sequences, and on systems in which N is a divisor of p. Our results deal primarily with the mean-square multiple-access interference and the signal-to noise ratio. We have found that in systems in which N and p are relatively prime, the resulting loss of control of sequence phases leads to an increase in the multiple-access interference of about 15 percent over systems in which $p = N$ and which employ signature sequences in their optimal phases. On the

other hand, systems in which N is a divisor of p perform in a similar manner to systems in which $p = N$. It is, of course, difficult to optimize phases for sequences of long period. However, we have derived a method of sequence design which enables us to construct long sequences and achieve the desired performance without any optimization of phases.

We have designed classes of quadriphase sequences for use in DS/SSMA systems using QPSK or offset-QPSK modulation. Our results enable us to design sets of sequences containing $2(N+1)$ sequences of period N for which the maximum magnitudes of the periodic correlation functions are bounded by $3(N+1)^{1/2}+5$. Here, N is a multiple of 4, and $N+1$ is a prime or prime power. It is also possible to design smaller sets of sequences for which the autocorrelation properties are nearly ideal. These sets are analogous to the maximal connected sets of binary m-sequences.

We have obtained new classes of bounds on the aperiodic autocorrelation and crosscorrelation functions for shift register sequences. Using results on the ambiguity functions and the *periodic* correlation functions for shift register sequences, we have been able to obtain bounds on the aperiodic correlation functions. For m-sequences and Kasami sequences, these bounds improve on the results of Niederreiter and of McEliece. However, the bound for Kasami sequences is significantly weaker than the bound for m-sequences. Using an alternative approach based on the mean-square correlation properties of shift register sequences, we have been able to show that given any offset and any m-sequence of period N there exists a phase of the m-sequence such that the aperiodic autocorrelation magnitude for that offset is no larger than $\frac{1}{2}N^{1/2}$. Using this result, we have shown that there exist phases of the given m-sequence with merit factor greater than 3. Such results are of considerable interest (the bounds, for example, are much tighter than the ones discussed above), but they do require searching among the phases of the m-sequence. Similar results have been obtained for Gold sequences also. We have also shown that the Gold sequences constitute a class of complementary sequences.

Coding for Frequency-Hop Spread-Spectrum Radio Networks

Much of our initial work in this area was concerned with error probabilities and local throughput for a slotted random-access communication system with frequency-hopped spread-spectrum modulation and error-control coding. Two different models for the channel traffic have been studied. The first is an infinite population of terminals modeled as Poisson traffic, and the second is a finite population for which the traffic levels are governed by the binomial distribution. In all cases, asynchronous transmission and frequency hopping are assummed. The networks considered are those that operate in a packet broadcasting mode: each packet that is transmitted is "heard" by every receiver within range of the transmitter. This does not say that each receiver within range is able to despread and demodulate the packet. But the signal is present in the front end of the receiver of all terminals within range and is therefore a potential source of interference for such terminals.

We have found that the combination of frequency-hopping and Reed-Solomon coding permits reliable communication among a large number of terminals even though the terminals operate asynchronously and transmit simulaneously. The throughput is improved greatly through the use of side information, which is used for erasing symbols which have been hit by multiple-access interference. It has been shown that for any value of codeword error probability less than 0.1, systems with frequency-hopping and Reed-Solomon coding have much greater throughput per frequency slot that an uncoded system without frequency-hopping (*i.e.*, standard slotted ALOHA). On the basis of these results, we claim that for codeword error probabilities of interest, frequency-hop spread spectrum is actually bandwidth efficient in comparison to standard slotted ALOHA.

More recently, we have completed a comprehensive investigation of the performance of frequency-hop transmission in a packet communication network. Satellite multiple-access broadcast channels for packet switching and terrestrial packet radio networks are the primary examples of the type of network considered. An analysis of the effects of multiple-access interference in frequency-hop radio networks is presented. New measures of "local" performance are defined and evaluated for a network of this type, and new concepts that are important in the design of these networks are introduced. In particular, error probabilities and local throughput are evaluated for a frequency-hop radio network which incorporates the standard slotted and unslotted ALOHA channel-access protocols, asynchronous frequency hopping, and Reed-Solomon error-control coding. The performance of frequency-hop

multiple access with error-control coding is compared with the performance of conventional ALOHA random access using narrowband radios.

Time Hopping Multiple-Access Communication

Time-hopping multiple-access (THMA) communication is a multiple-access packet communication scheme suitable for use in systems using the slotted ALOHA protocol for channel access. In THMA schemes, each packet is encoded with an interleaved (n, k) Reed-Solomon code and broken up into n subpackets that are transmitted at different times in accordance with a *time-hopping pattern*. Thus, a packet is received correctly unless it suffers more than $n-k$ subpacket collisions. Although the maximum throughput for THMA is smaller than that for slotted ALOHA, THMA has considerably higher throughput than slotted ALOHA when channel traffic is low. For most pure-contention channel-access protocols, the maximum throughput occurs at packet error rates that are too high for packet radio applications. If the packet error rate is required to be less than 10^{-2} (this implies that channel traffic must be quite low), then THMA can have throughput which is an order of magnitude larger than that for slotted ALOHA. On the other hand, THMA involves longer delays in transmission than slotted ALOHA because of the time-hopping. Also, the THMA system analyzed has considerably more stringent requirements on synchronization because the subpacket duration is smaller by a factor of k compared to the packet duration in slotted ALOHA.

LIST OF PARTICIPATING PERSONNEL

Co-Principal Investigators

Professor Michael B. Pursley
Professor Dilip V. Sarwate
Professor Robert J. McEliece

Graduate Research Assistants and Degrees Earned

D. E. Borth	Ph.D.	in Electrical Engineering
F. D. Garber	Ph.D.	in Electrical Engineering
E. A. Geraniotis	M. S.	in Electrical Engineering
	Ph.D.	in Electrical Engineering
D. W. Gahutu	M. S.	in Electrical Engineering
C. M. Keller	M. S.	in Electrical Engineering
S. M. Krone	M. S.	in Electrical Engineering
A. W. Lam	M. S.	in Electrical Engineering
J. S. Lehnert	M. S.	in Electrical Engineering
	Ph.D.	in Electrical Engineering
J. Y. Park		
P. D. Rasky	M. S.	in Electrical Engineering
M. S. Schmidt	M. S.	in Electrical Engineering
W. E. Stark	M. S.	in Electrical Engineering
	Ph.D.	in Electrical Engineering
D. J. Taipale	M. S.	in Electrical Engineering

PUBLICATIONS SUPPORTED BY ARO GRANT DAAG29-78-G-0114 AND ARO CONTRACT DAAG29-81-K-0064

Chapters in Books

M. B. Pursley, "Spread-spectrum multiple-access communications," in *Multi-User Communication Systems*, G. Longo, Ed., (Springer-Verlag: New York), pp. 139-199, 1981.

Journal Articles

M. B. Pursley and H. F. A. Roefs, "Numerical evaluation of correlation parameters for optimal phases of binary shift-register sequences," *IEEE Transactions on Communications*, Vol. COM-27, pp. 1597-1604, October 1979.

D. V. Sarwate and M. B. Pursley, "Crosscorrelation properties of pseudorandom and related sequences," (Invited Paper) *Proceedings of the IEEE*, Vol. 68, pp. 593-619, May 1980.

F. D. Garber and M. B. Pursley, "Optimal phases of maximal-length sequences for asynchronous spread-spectrum multiplexing," *Electronics Letters*, Vol. 16, pp. 756-757, September 1980.

F. D. Garber and M. B. Pursley, "Performance of offset quadriphase spread-spectrum multiple-access communications," *IEEE Transactions on Communications*, Vol. COM-30, pp. 305-314, March 1981.

W. E. Stark and D. V. Sarwate, "Kronecker sequences for spread-spectrum communication," *IEE Proceedings – Part F: Communications, Radar, and Signal Processing*, Vol. 128, pp. 104-109, April 1981.

M. B. Pursley, D. V. Sarwate, and W. E. Stark, "Error probability for direct-sequence spread-spectrum multiple-access communications – Part I: Upper and lower bounds," *IEEE Transactions on Communications*, Vol. COM-30, pp. 978-984, May 1982.

E. A. Geraniotis and M. B. Pursley, "Error probability for direct-sequence spread-spectrum multiple-access communications – Part II: Approximations," *IEEE Transactions on Communications*, Vol. COM-30, pp. 985-995, May 1982.

D. V. Sarwate, "Sets of complementary sequences," *Electronics Letters*, Vol. 19, pp. 711-712, September 1983.

D. V. Sarwate, "Mean square correlation of shift register sequences," *IEE Proceedings – Part F: Communications, Radar, and Signal Processing*, Vol. 131, pp. 101-106, April 1984.

S. M. Krone and D. V. Sarwate, "Quadriphase sequences for spread-spectrum multiple-access communication," *IEEE Transactions on Information Theory*, Vol. IT-30, pp. 520-529, May 1984.

D. V. Sarwate, M. B. Pursley, and T. U. Basar, "Partial correlation effects in direct-sequence spread-spectrum multiple-access communication systems," *IEEE Transactions on Communications*, Vol. COM-32, pp. 567-573, May 1984.

D. V. Sarwate, "An upper bound on the aperiodic autocorrelation function for a maximal-length sequence," *IEEE Transactions on Information Theory*, Vol. IT-30, pp. 685-687, July 1984.

M. B. Pursley, "Frequency-hop transmission for satellite packet switching and terrestrial packet radio networks," submitted for publication to the *IEEE Transactions on Information Theory*, July 1984.

Conference Papers

D. V. Sarwate, "Cross-correlation properties of sequences with applications to spread-spectrum multiple-access communication," (Invited Paper) *Proceedings of the AFOSR Workshop in Communication Theory and Applications*, (Provincetown, Massachusetts: September 17-20, 1978), pp. 88-91.

D. V. Sarwate, "Optimal crosscorrelation properties of sequences for spread-spectrum multiplexing," *Proceedings of the 1979 Conference on Information Sciences and Systems*, (The Johns Hopkins

University, Baltimore, Maryland: March 28-30, 1979), pp. 141-143.

M. B. Pursley, "Large time-bandwidth product signals for spread-spectrum multiple-access communications," (Invited Paper) *1979 International IEEE/APS Symposium and National Radio Science Meeting*, (Seattle, Washington: June 1979), p. 137.

D. E. Borth, M. B. Pursley, D. V. Sarwate, and W. E. Stark, "Bounds on error probability for direct-sequence spread-spectrum multiple-access communication," (Invited paper) *MIDCON Proceedings*, (Chicago, Illinois: November 6-8, 1979), p. 15/1.

M. B. Pursley, W. E. Stark, and D. V. Sarwate, "On the average probability of error for direct-sequence spread-spectrum multiple-access systems," *Proceedings of the 1980 Conference on Information Sciences and Systems*, (Princeton University, Princeton, New Jersey: March 26-28, 1980), pp. 320-325.

M. B. Pursley, F. D. Garber, and J. S. Lehnert, "Analysis of generalized quadriphase spread-spectrum communications," (Invited Paper) *Conference Record, IEEE International Conference on Communications*, (Seattle, Washington: June 8-12, 1980), Vol. 1, pp. 15.3.1-6.

D. V. Sarwate and M. B. Pursley, "New results on frequency-hopped patterns for spread-spectrum multiple-access communications," (Invited paper) *Conference Record, IEEE International Conference on Communications*, (Seattle, Washington: June 8-12, 1980), p. 15.2.1.

E. A. Geraniotis and M. B. Pursley, "Performance analysis for fast-frequency-hopped spread-spectrum multiple-access communications," *Conference Record, IEEE National Telecommunications Conference*, (Houston, Texas: December 1-4, 1980), Vol. 1, pp. 17.4.1-5.

E. A. Geraniotis and M. B. Pursley, "Error probability for binary PSK spread-spectrum multiple-access communications," *Proceedings of the Seventeenth Annual Conference on Information Sciences and Systems*, (The Johns Hopkins University, Baltimore, Maryland: March 25-27, 1981), pp. 238-244.

M. B. Pursley, "Effects of partial correlation on the multiple-access capability of direct-sequence spread-spectrum," *Conference Record, IEEE National Telecommunications Conference*, (New Orleans, Louisiana: November 29 - December 3, 1981), Vol. 2, pp. D4.3.1-5.

M. B. Pursley, "Coding and diversity for channels with fading and pulsed interference," *Proceedings of the 1982 Conference on Information Sciences and Systems*, (Princeton University, Princeton, New Jersey: March 17-19, 1982), pp. 413-418.

E. A. Geraniotis and M. B. Pursley, "Effects of specular multipath fading on noncoherent direct-sequence spread-spectrum communications," *Conference Record, IEEE International Conference on Communications*, (Philadelphia, Pennsylvania: June 13-17, 1982), Vol. 3, pp. 6B.5.1-5.

W. E. Stark, "Performance of concatenated codes on channels with jamming," *Conference Record, IEEE International Conference on Communications*, (Philadelphia, Pennsylvania: June 13-17, 1982), Vol. 3, pp. 7E.4.1-5.

S. M. Krone and D. V. Sarwate, "Quadriphase sequences for spread-spectrum communications," *Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory*, (Les Arcs, France: June 21-25, 1982), pp. 42-43.

R. J. McEliece and M. B. Pursley, "Error-control coding for slow-frequency-hopped spread-spectrum communications," *Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory*, (Les Arcs, France: June 21-25, 1982), p. 42.

W. E. Stark, "Coding for coherent frequency-hopped spread-spectrum communication in the presence of jamming," *Proceedings of the 1982 IEEE Military Communications Conference*, (Boston, Massachusetts: October 18-20, 1982), Vol. 1, pp. 14.2.1-5.

T. U. Basar and D. V. Sarwate, "New results on partial correlation properties of sequences," *Proceedings of the Seventeenth Annual Conference on Information Sciences and Systems*, (The Johns Hopkins University, Baltimore, Maryland: March 23-25, 1983), pp. 767-769.

M. B. Pursley, "Throughput of frequency-hopped spread-spectrum communications for packet radio networks," *Proceedings of the Seventeenth Annual Conference on Information Sciences and Systems*, (The Johns Hopkins University, Baltimore, Maryland: March 23-25, 1983), pp. 550-556.

M. B. Pursley, "Throughput of random-access frequency-hopped communications," *Abstracts of Papers for the 1983 IEEE International Symposium on Information Theory*, (St. Jovite, Quebec, Canada: September 26-30, 1983), pp. 99-100.

D. V. Sarwate, "Aperiodic correlation properties of sequences," (Invited Paper) *National Radio Science Meeting*, (Boulder, Colorado: January 11-14, 1984), p. 158.

P. D. Rasky and D. V. Sarwate, "Performance analysis of a time-hopping multiple-access communication scheme," to appear in *Proceedings of the Eighteenth Annual Conference on Information Sciences and Systems*, (Princeton University, Princeton, New Jersey: March 14-16, 1984).

D. V. Sarwate, "Construction of complementary code sequence sets," to appear in *Middle Atmosphere Program Handbook XII: Proceedings of the Second Conference on Technical Aspects of MST Radar*, (URSI Scientific Committee on Solar-Terrestrial Physics, Urbana, Illinois: May 22-25, 1984).

Technical Reports

D. W. H. Gahutu, "On correlation parameters for some binary sequences of lengths 31 and 63 for spread-spectrum multiple-access communications," Report R-845 (UILU-ENG 78-2238), Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, May 1979.

W. E. Stark, "Kronecker sequences for spread-spectrum communications," Report T-86, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, August 1979.

J. S. Lehnert, "Chip waveform selection in offset-quaternary direct-sequence spread-spectrum multiple-access communications," Report R-907 (UILU-ENG 81-2238), Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, January 1981.

S. M. Krone, "Quadriphase sequences for spread-spectrum communication," Report T-118, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois.

P. D. Rasky, "A multiple access communications scheme using time hopping and error control coding," Report T-134, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, January 1984.